DETAILED DESCRIPTION

It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, or a computer readable medium such as a computer readable storage medium or a computer network wherein program instructions are sent over optical or electronic communication links. It should be noted that the order of the steps of disclosed processes may be altered within the scope of the invention.

A detailed description of one or more preferred embodiments of the invention is provided below along with accompanying figures that illustrate by way of example the principles of the invention. While the invention is described in connection with such embodiments, it should be understood that the invention is not limited to any embodiment. On the contrary, the scope of the invention is limited only by the appended claims and the invention encompasses numerous alternatives, modifications and equivalents. For the purpose of example, numerous specific details are set forth in the following description in order to provide a thorough understanding of the present invention. The present invention may be practiced according to the claims without some or all of these specific details. For the purpose of clarity, technical material that is known in the technical fields related to the invention has not been described in detail so that the present invention is not unnecessarily obscured.

In a typical system as described below, bits representing a set of data that is to be communicated are convolutionally encoded or otherwise transformed into values.

Various types of modulation may be used such as BPSK, QPSK, 16QAM or 32QAM. In the case of BPSK, which is described further herein, each BPSK symbol may have one of two values and each BPSK symbol corresponds to one bit. An OFDM symbol includes 48 values that are transmitted on different subchannels. To provide extended range, each value that is sent is repeated several times by the transmitter. In one embodiment, the bits are convolutionally encoded using the same encoding scheme as the encoding scheme specified for the IEEE 802.11a/g standard. Each encoded value is repeated and transmitted. Preferably, the values are repeated in the frequency domain, but the values may also be repeated in the time domain. In some embodiments, the repetition coding is implemented before interleaving and a specially designed interleaver is used to handle repeated values. In addition, a pseudorandom code may be superimposed on the OFDM symbols to lower the peak to average ratio of the transmitted signal.

The receiver combines each of the signals that correspond to the repetition coded values and then uses the combined signal to recover the values. In embodiments where the values are combined in the frequency domain, the signals are combined coherently with correction made for different subchannel transfer functions and phase shift errors. For the purpose of this description and the claims, "coherently" combining should not be interpreted to mean that the signals are perfectly coherently combined, but only that some phase correction is implemented. The signals from different subchannels are weighted according to the quality of each subchannel. A combined subchannel weighting is provided to a Viterbi detector to facilitate the determination of the most likely transmitted sequence.

Using the modulation and encoding scheme incorporated in the IEEE 802.11a/g standard, the required signal to noise ratio decreases linearly with data rate assuming the same modulation technique and base code rate are not changed and repetition coding is used. Some further gains could be achieved through the use of a better code or outer code. However, in a dual mode system that is capable of implementing both the IEEE 802.11a/g standard and an extended range mode, the complexity introduced by those techniques may not be worth the limited gains that could be achieved. Implementing repetition of values is in comparison simpler and more efficient in many cases.

The repetition code can be implemented either in the time domain or in the frequency domain. For time domain repetition, the OFDM symbols in the time domain (after the IFFT operation) are repeated a desired number of times, depending on the data rate. This scheme has an advantage in efficiency since just one guard interval is required for r-repeated OFDM symbols in the time domain.

Figure 1A is a diagram illustrating the data portion of a regular 802.11a/g OFDM packet. Each OFDM symbol 102 is separated by a guard band 104. Figure 1B is a diagram illustrating the data portion of a modified 802.11a/g OFDM packet where each symbol is repeated twice (r=2). Each set of repeated symbols 112 is separated by a single guard band 104. There is no need for a guard band between the repeated symbols.

The OFDM symbols can also be repeated in the frequency domain (before the IFFT). The disadvantage of this scheme is that one guard interval has to be inserted between every OFDM symbol in the time-domain since the OFDM symbols with

frequency-domain repetition are not periodic. However, repetition in the frequency domain can achieve better multipath performance if the repetition pattern is configured in the frequency-domain to achieve frequency diversity.

In a typical environment where signals are reflected one or more times between the transmitter and the receiver, it is possible that certain reflections and direct signals will tend to cancel out at the receiver because the phase difference between the paths could be close to 180 degrees. For different frequencies, the phase difference between the paths will be different and so spreading the repeated values among different frequencies to achieve frequency diversity ensures that at least some of the values will arrive at the receiver with sufficient signal strength to be combined and read. To maximize the benefit of frequency diversity, it is preferable to repeat values across subchannels that are as widely spaced as is practicable, since the phase difference between adjacent subchannels is small.

Figure 2A is a diagram illustrating a transmitter system with a repetition encoder placed after the output of an interleaver such as the one specified in the IEEE 802.11a/g specification. In this example system, BPSK modulation is implemented and the repetition encoder and the interleaver are described as operating on bits, which is equivalent to operating on the corresponding values. In other embodiments, other modulation schemes may be used and values may be repeated and interleaved. The interleaver is included in the IEEE 802.11a/g transmitter specification for the purpose of changing the order of the bits sent to remove correlation among consecutive bits introduced by the convolutional encoder. Incoming data is convolutionally encoded by

convolutional encoder 202. The output of convolutional encoder 202 is interleaved by IEEE 802.11a/g interleaver 204. Repetition encoder 206 repeats the bits and pseudorandom mask combiner 208 combines the output of repetition encoder 206 with a pseudorandom mask for the purpose of reducing the peak to average ratio of the signal, as is described below. The signal is then processed by IFFT processor 210 before being transmitted.

Figure 2B is a diagram illustrating a receiver system for receiving a signal transmitted by the transmitter system depicted in Figure 2A. The received signal is processed by FFT processor 220. The output of FFT processor 220 is input to mask remover 218 which removes the pseudorandom mask. Data combiner 216 combines the repetition encoded data into a stream of nonrepetitive data. The operation of data combiner 216 is described in further detail below. IEEE 802.11a/g deinterleaver 214 deinterleaves the data and Viterbi decoder 212 determines the most likely sequence of data that was input to the transmission system originally.

The system depicted in Figures 2A and 2B can use the same interleaver and deinterleaver as the regular 802.11a/g system, and also has flexibility in designing the repetition pattern since the repetition coder is placed right before the IFFT block. However, it has certain disadvantages. Data padding is required at the transmitter and data buffering is required at the receiver. Bits have to be padded according to the number of bytes to be sent and the data rate. The number of padded bits is determined by how many bits one OFDM symbol can carry. Since the 802.11a/g interleaver works with 48 coded bits for BPSK modulation, bits need to be padded to make the number of coded

bits a multiple of 48. Since the repetition coder is placed after the interleaver, it may be necessary to pad the data by adding unnecessary bits for lower data rates than 6Mbps.

For example, one OFDM symbol would carry exactly 1 uncoded repeated bit at a data rate of 1/4Mbps. Since the OFDM symbol could be generated from that one bit, there would never be a need to add extra uncoded bits and so padding would not be necessary in principle. However, due to the special structure of the 802.11a/g interleaver, several bits would need to be padded to make the number of coded bits a multiple of 48 before the interleaver. The padded bits convey no information and add to the overhead of the transmission, making it more inefficient.

On the other hand, if the repetition encoder is placed after the interleaver, the repetition coded bits generated from the 48 interleaved bits are distributed over multiple OFDM symbols. Therefore, the receiver would need to process the multiple OFDM symbols before deinterleaving the data could be performed. Therefore, additional buffers would be necessary to store frequency-domain data.

The system can be improved and the need for data padding at the transmitter and data buffering at the receiver can be eliminated by redesigning the interleaver so that it operates on bits output from the repetition encoder.

Figure 3A is a diagram illustrating a transmitter system with a repetition encoder placed before the input of an interleaver designed to handle repetition coded bits such as the one described below. Incoming data is convolutionally encoded by convolutional encoder 302. The output of convolutional encoder 302 is repetition coded by repetition

encoder 304. Interleaver 306 interleaves the repetition coded bits. Interleaver 306 is designed so that data padding is not required and so that for lower repetition levels, the bits are interleaved so as to separate repeated bits. Pseudorandom mask combiner 308 combines the output of Interleaver 306 with a pseudorandom mask for the purpose of reducing the peak to average ratio of the signal, as is described below. The signal is then processed by IFFT processor 310 before being transmitted.

Figure 3B is a diagram illustrating a receiver system for receiving a signal transmitted by the transmitter system depicted in Figure 3A. The received signal is processed by FFT processor 320. The output of FFT processor 320 is input to mask remover 318 which removes the pseudorandom mask. Deinterleaver 316 deinterleaves the data. Data combiner 314 combines the repetition encoded data into a stream of nonrepetitive data. The operation of data combiner 314 is described in further detail below. Viterbi decoder 312 determines the most likely sequence of data that was input to the transmission system originally.

Interleaver 306 is preferably designed such that the same (repeated) data are transmitted well separated in the frequency domain to achieve full frequency diversity. For example, a repetition pattern in the frequency domain for in 1 Mbps mode in one embodiment would repeat each bit 6 times. Denoting data in the frequency domain as $d_1, d_2, \cdots, d_8$, the repeated sequence of data is given by:

$$d_1\, d_1\, d_1\, d_1\, d_1\, d_1\, d_2\, d_2\, d_2\, d_2\, d_2\, d_2 \quad \cdots \quad d_8\, d_8\, d_8\, d_8\, d_8\, d_8$$